Graded-index Polymer Multimode Waveguides for 100 Gb/s Board-level Data Transmission

Jian Chen[(1)], Nikos Bamiedakis[(1)], Peter Vasil'ev [(1)], Tom J. Edwards[(2)], Christian T.A. Brown[(2)], Richard V. Penty[(1)], and Ian H. White[(1)]

[(1)] Electrical Engineering Division, Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, UK, email: jc791@cam.ac.uk

[(2)] SUPA, School of Physics & Astronomy, University of St Andrews, North Haugh, St Andrews, Fife, KY16 9SS, UK

Abstract *We report enhanced graded-index multimode polymer waveguides with >70GHz×m for MMF launch and >200GHz×m for restricted launch, indicating the capability of on-board waveguide transmission of >100 Gb/s. Simulations using the measured refractive index profile agree well with the experiments.*

Introduction

In recent years, short-reach optical interconnects have attracted significant research interests for use in board-level datacommunication links owing to their advantages over conventional electrical interconnects such as high bandwidth, high immunity to electromagnetic interference, reduced power consumption and high data density[1]. In particular, polymer multimode waveguides constitute an attractive technology as they can be directly integrated on printed circuits boards (PCBs) due to the favourable thermal and mechanical properties of appropriate optical polymer materials. Additionally, they offer relaxed alignment tolerances due to their large waveguide core dimensions (typical 30-70 μm). Vertical-cavity surface-emitting lasers (VCSELs) are the main sources for on-board optical interconnects owing to their low cost, high power efficiency and large bandwidth. Their bandwidth performance has continuously improved over the past few years, with up to 64 Gb/s direct modulation operation recently demonstrated[2]. Due to the highly-multimoded nature of these polymer waveguides, it therefore becomes crucial to investigate their bandwidth limits and assess their potential to support very high on-board data rates (>100 Gb/s).

In related studies on multimode polymer waveguides, bandwidth-length products (BLP) <100 GHz×m have been reported. For example, the estimated -3 dB bandwidth and BLP of the guides reported has been found to be 50 GHz for 30 cm (BLP: 15 GHz×m), 39 GHz for 1 m (BLP: 39 GHz×m) and 23 GHz for 2.55 m (BLP: 57.5 GHz×m) long waveguides under a single-mode fibre (SMF) launch[3]. The bandwidth performance of these waveguides has been found to be significantly affected by strong mode mixing with very short equilibrium lengths of ~10 cm observed. Larger values of 150 GHz (BLP: 75 GHz×m) for a 51 cm long waveguide[4] and 1.03 GHz (BLP: 90 GHz×m) for a 90 m long waveguide[5] have been reported for polymeric waveguides under a SMF launch. However, these studies mostly focus on restricted launches. We have recently presented bandwidth studies on a 1 m long polymer multimode spiral waveguide with a graded-index (GI) geometry using frequency domain (S_{21}) measurements, and demonstrated an instrument-limited BLP of at least 35 GHz×m under various launch conditions. 40 Gb/s data transmission over these long waveguides has been reported[6]. In this work, we present experimental and theoretical bandwidth studies on similar graded-index polymer multimode waveguides in order to investigate their ultimate bandwidth. Optical domain measurements reveal a BLP of >70 GHz×m under multi-mode fibre (MMF) launch and >200 GHz×m under a restricted launch. The refractive index profile of these waveguide is measured and a simulation model is developed. The simulation results agree well with the experimental observations, and indicate that, similarly to multimode fibres, particular range of input offsets can offer significant bandwidth performance improvement. These results clearly demonstrate that data transmission at rates >100 Gb/s over a single such waveguide is feasible.

Graded-index waveguide samples

The waveguides are fabricated from siloxane materials on 8-inch silicon substrates using conventional photolithography. The core and cladding are Dow Corning® WG-1020 Optical Waveguide Core and XX-1023 Optical Waveguide Clad respectively. The spiral waveguides have a cross section of ~32×36 μm^2 and are 105.5 cm in length while they are fabricated to have a graded-like index profile by controlling the fabrication parameters[7]. A top view of the spiral waveguide and an image of the waveguide output are shown in Fig. 1. The refractive index (RI) profile of the waveguide is measured using the refractive near field method and is shown in Fig. 2.

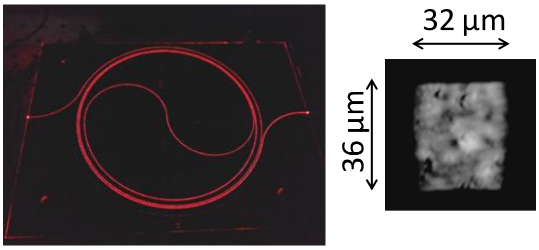

Fig. 1: (a) The 1 m long spiral waveguide illuminated with red light and (b) near field image of the waveguide output.

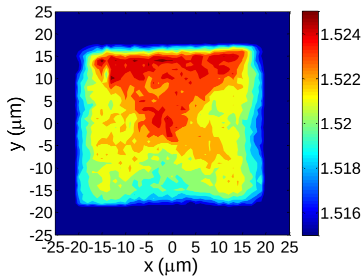

Fig. 2: Measured RI profile of the waveguide at 678 nm.

Experimental setup and results

Pulse broadening measurements have been carried using two different short pulse generation systems. One uses a Ti:Sapphire laser operating at 850 nm and a FR103-MN autocorrelator while the other utilises a femtosecond erbium-doped fibre laser source operating at ~1574 nm and a frequency-doubling crystal (MSHG1550-0.5-1) to generate pulses at wavelength of ~787 nm. A matching autocorrelator is used to detect the transmitted optical pulses.

The pulse broadening in the waveguides is studied under different launch conditions, ranging from restricted to overfilled (Fig. 3), as the dispersion in such highly-multimoded waveguide is strongly dependent on the type of spatial excitation. Moreover, different launch positions generate different mode power distributions at the waveguide input and can therefore, significantly affect the observed bandwidth performance. The launch conditions studied in this work include (ranging from more restricted to more overfilled): (1) a 10× microscope objective; (2) a "typical" 50/125 µm MMF (NA=0.2); and (3) a 50/125 µm MMF with a mode mixer (MM). The generated short pulses are coupled to the waveguide input using a short cleaved patchcord. For launch condition (3), a mode mixer (Newport FM-1) is used to generate a more uniform power distribution in the input 50/125 µm MMF. The launch position is controlled via a translation stage and a displacement sensor. The light at the output of the waveguide is collected with a 16x microscope objective (NA=0.32) to avoid mode selective loss, and is delivered to the autocorrelator using free-space elements. The autocorrelation traces of received pulses after transmission over the 1 m long spiral waveguide as well as the back-to-back configuration (i.e. without the waveguide) are recorded.

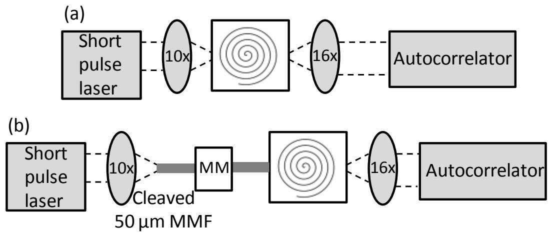

Fig. 3: Experimental setup for launch conditions (1) and (3): (a) a 10x microscope objective launch and (b) a 50/125 µm MMF launch with the mode mixer (MM).

The received signal pulses are estimated from the recorded autocorrelation traces using curve fitting with common pulse shapes (i.e. $sech^2$, Gaussian or Lorentzian). The frequency responses of the back-to-back and waveguide link are then calculated using the Fourier transform, and the waveguide frequency response is obtained by taking their difference. The -3 dB bandwidth of the 1 m long spiral waveguide is found for each launch condition studied and the different input positions (Fig. 4). It should be noted that the measurement for launch (1) (lens input) is conducted at ~787 nm whereas the measurements for launches (2) and (3) (MMF inputs) are carried out at 850 nm.

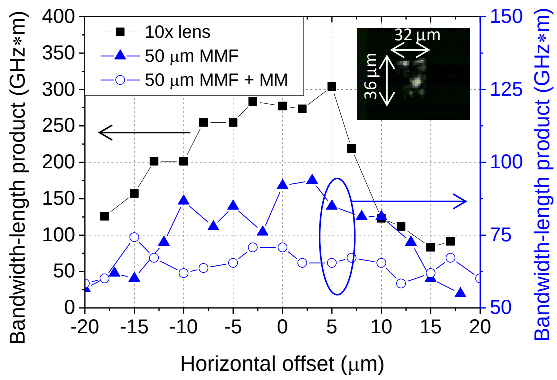

Fig. 4: Bandwidth-length product for launch conditions: (a) 10x lens (launch 1) (b) "typical" 50/125 µm MMF (launch 2); (c) 50/125 µm MMF with mode mixer (launch 3). Inset image shows waveguide output under launch (1).

The lens launch yields a very large BLP of >200 GHz×m with an alignment tolerance of ≤±5 µm owing to the excitation of limited modes at the waveguide input. A near field image of the waveguide output (inset Fig. 4) confirms the observation showing clear restricted mode group excitation. The obtained BLP is >70

GHz×m for the "typical" 50/125 μm MMF launch for input offsets ≤±10 μm, while the use of the mode mixer results in a slightly reduced BLP of >60 GHz×m due to the induced more uniform excitation at the waveguide input. Overall, the measurements demonstrate a very large BLP in excess of 60 GHz×m for these GI waveguides and indicate the possibility of transmitting >100 Gb/s data rates over a single waveguide.

Waveguide modelling

Simulation studies are carried out to confirm the obtained bandwidth performance. A commercial mode solver (FIMMWAVE) is used to calculate the waveguide modes and their effective and group refractive indices. The mode power distribution inside the waveguide is calculated using overlap integrals of the electric fields of the input fibre modes and waveguide modes at the waveguide input[8]. The impulse response of the waveguide, and therefore the waveguide bandwidth, can be found by calculating the intermodal dispersion in the guide. The simulation model is based on a straight waveguide (no bending losses assumed) and the simplistic assumption that no mode mixing takes place in the guide.

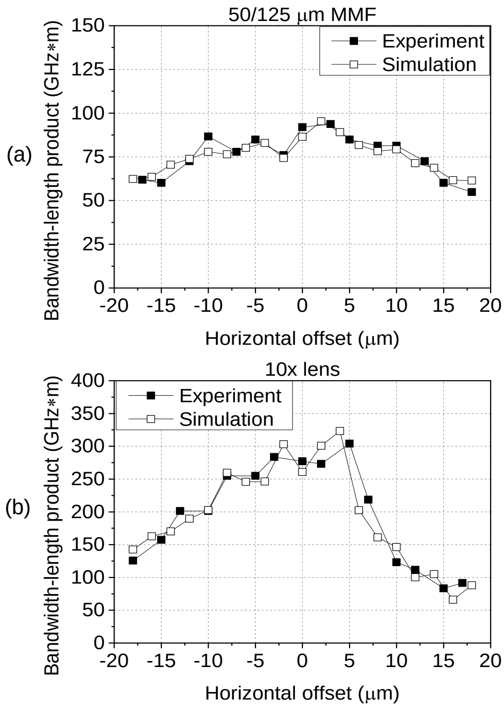

Fig. 5: Simulation and experimental results for (a) a 50/125 μm MMF launch and (b) a 10x lens launch.

The simulation results indicate a BLP of >70 GHz×m for a MMF launch and >200 GHz×m for a restricted (10x lens input) launch. The calculated BLP for an overfilled launch is found to be ~60 GHz×m which agrees well with the experimentally-observed values. Fig. 5 shows the simulated and experimental bandwidth-length products for different positions of a MMF and a 10x lens input. The simulation and experimental results exhibit similar trends of bandwidth variation across offsets and indicate that launch conditioning in such guides can have a significantly beneficial effect on bandwidth performance.

Conclusions

Pulse broadening measurements have been conducted on GI waveguides under different launch conditions. Bandwidth-length products of >60 GHz×m with a "quasi-overfilled" launch, >70 GHz×m with a "typical" 50/125 μm MMF launch for input offsets ≤±10 μm and >200 GHz×m with a 10x microscope objective launch for input offsets ≤±5 μm have been measured. A model is used to calculate the BLP of these guides using their measured refractive index profile. The modelling agrees well with the experimental results demonstrating the potential of this technology, to achieve data transmission of >100 Gb/s over a single waveguide using appropriate launch conditioning schemes.

Acknowledgements

The authors would like to acknowledge Dow Corning for providing the waveguide samples and EPSRC for supporting the work. Data related to this publication is available at the University of Cambridge data repository.

References

[1] N. Bamiedakis et al., "Bandwidth studies on multimode polymer waveguides for ≥ 25 Gb/s optical interconnects," IEEE Photon. Technol. Lett., Vol. **26**, no. 20, pp. 2004–2007 (2014).

[2] D. Kuchta et al., "64 Gb/s Transmission over 57m MMF using an NRZ Modulated 850nm VCSEL," Proc. OFC, Th3C.2, San Francisco (2014).

[3] F. E. Doany et al., "Measurement of optical dispersion in multimode polymer waveguides," in IEEE/LEOS Summer Topical Meetings Tech. Dig., MB4.4, San Diego (2004).

[4] W. Xiaolong et al., "Hard-molded 51 cm long waveguide array with a 150 GHz bandwidth for board-level optical interconnects," Opt. Lett., Vol. **32**, pp. 677–679 (2007).

[5] T. Kosugi et al., "Polymer parallel optical waveguide with graded-index rectangular cores and its dispersion analysis," Opt. Express, Vol.**17**, pp.15959-15968 (2009).

[6] N. Bamiedakis et al., "40 Gb/s Data Transmission Over a 1 m Long Multimode Polymer Spiral Waveguide for Board-Level Optical Interconnects," J. Lightwave Technol., Vol. **33**, no.4, pp. 1-7 (2015).

[7] B.W. Swatowski et al., "Graded index silicone waveguides for high performance computing," in Proc. IEEE Opt. Interconnects Conf., WD2, San Diego (2014).

[8] P. Pepeljugoski et al., "Modeling and simulation of next-generation multimode fiber links," J. Lightwave Technol., Vol. **21**, pp. 1242–1255 (2003).